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On the Permissible Roughness in the Laminar Boundary Layer.

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Abstract.

Schiller suggested that the critical height of the excrescence that disturbs the laminar boundary layer and causes its transition to turbulent flow is the height at which vortices form behind the excrescence. From this it follows that the permissible roughness k in the laminar boundary layer is given by $k(\tau_0/\rho)^{\frac{1}{2}}/\nu = K$, where τ_0 is the shearing stress at the surface, and K is a certain constant, although little is known about the magnitude of K. Wind tunnel experiments were therefore made in order to determine the value of K on a flat plate and on a symmetrical aerofoil, the roughness being simulated by a wire of diameter k. It was found that $K = 13$ for the flat plate, and $K = 15$ for the aerofoil. By adopting the lower value for K, for safety, it is possible to estimate the magnitude of the permissible roughness on the surface of a body of any shape.

Introduction.

It is well known that even a small degree of surface roughness causes serious increase in drag, which increase is due partly to the direct drag of the excrescences themselves, and partly to the premature transition from laminar to turbulent flow in the boundary layer caused by the excrescences, when they form ahead of the transition point for the smooth surface. Interesting data on the drag of excrescences in the turbulent boundary layer have been obtained by Nikuradse[1] and Schlichting[2] from experiments on roughened pipes, and by Hood[3] and Young[4] from experiments on roughened aerofoils. Very little, however, is known regarding the permissible magnitude of excrescence beyond which the transition moves forward. For the aerofoil of a modern aeroplane, the mean position of the transition has been estimated at about 20 per cent of the chord from the leading edge, provided the surface is smooth. It may be possible to design aerofoil in such a way that the transition will be delayed beyond points hitherto observed, but granting that such far-back transition can actually be attained in some way in the near future, the first requisite is that the surface of the aerofoil shall be so smooth as not to disturb the position of transition. An attempt was therefore made to estimate the approximate order of magnitude of the permissible roughness in laminar boundary layers.

Schiller's suggestion.

Schiller[5] suggested that the critical height of the excrescence that alters the character of the flow is the height at which vortices form

(1) J. Nikuradse, Strömungsgesetze in rauhen Rohren. Forsch.-Arb. Ing.-Wes. Heft 361 (1933).

(2) H. Schlichting, Experimentelle Untersuchungen zum Rauhigkeitsproblem. Ingenieur-Archiv Bd. 7 (1936), S. 1.

(3) M. J. Hood, The effects of some common surface irregularities on wing drag. N.A.C.A. Tech. Note No. 695 (1939).

(4) A. D. Young, Surface finish and performance. Aircraft Engineering vol. 11 (1939), p. 339.

(5) L. Schiller, Handbuch der Experimentalphysik, Bd. 4, Teil 4 (1932), S. 191.

behind that excrescence. Constructing a Reynolds number from the height of excrescence k and the velocity at its top u_k, he found that there probably exists a critical value R_{crit} such that for $ku_k/\nu > R_{crit}$ vortices form behind the excrescence, whereas for $ku_k/\nu < R_{crit}$ the flow closes up behind. The exact value of R_{crit} is not known, but it is not likely to differ much from the critical Reynolds number for the uniform flow past an obstacle of the same shape as that of the excrescence. We may take, for example, $R_{crit} = 50$ for a circular cylinder, and $R_{crit} = 30$ for a flat plate placed normal to the flow.

Assuming that the height of excrescence k is small, and that the presence of the excrescence in no way alters the character of the flow, the shearing stress at the surface is given by $\tau_0 = \mu(u_k/k)$. Using the so-called friction velocity $v_* = (\tau_0/\rho)^{\frac{1}{2}}$ instead of u_k, Goldstein(1) suggested that the critical condition that the excrescence shall not disturb the flow can be expressed in such a form that kv_*/ν is less than $(R_{crit})^{\frac{1}{2}}$, or, if with $R_{crit} = 50$, less than about 7.

Experiments on a flat plate.

Since the foregoing estimate is based on nothing but mere conjecture, wind tunnel experiments were made to determine the permissible roughness on a flat plate and on a symmetrical aerofoil.

When a flat plate is placed along a uniform flow of velocity V, Blasius's solution of the boundary layer equation gives

$$v_* = 0{\cdot}576\,V\left(\frac{Vx}{\nu}\right)^{-\frac{1}{4}}$$

for a point of distance x from the leading edge. Writing K for the critical value of kv_*/ν, the permissible height of excrescence k is given by

$$0{\cdot}576\,\frac{k}{x} = K\left(\frac{Vx}{\nu}\right)^{-\frac{3}{4}}.$$

(1) S. Goldstein, A note on roughness. A.R.C., R. & M. No. 1763 (1937).

Although K is about 7 according to the above estimate, it may best be determined from experiments.

A polished aluminium plate, 80 cm long, 60 cm wide, and 3 mm thick, was held horizontally in the 1·5 m wind tunnel of the Institute. So that the flow at entry shall not be disturbed, the leading edge of the plate was rounded, and the plate slightly tilted so that the forward stagnation point was on the same surface as that where the observation was made. The tilting, however, was so slight that the static pressure

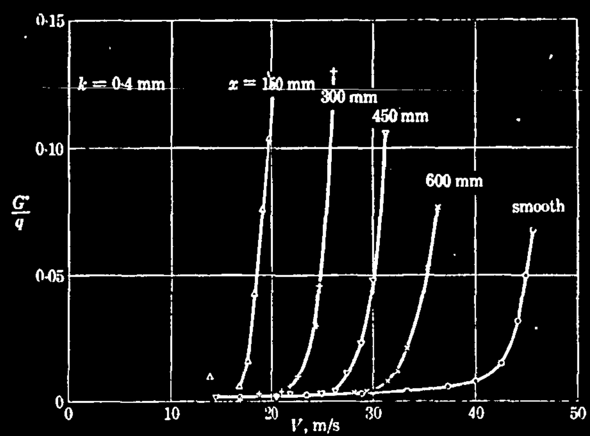

Fig. 1. Variation with wind speed V of the total pressure G^*, which is indicated by a small pitot tube in contact with the flat plate. A wire of 0·4 mm diameter is placed at various distances x from the leading edge. $q=(1/2)\rho V^2$.

was observed to be practically uniform along the plate. The degree of turbulence in the wind tunnel was fairly low, the transition Reynolds number for the flat plate being 2×10^6 (1), so that the boundary layer was entirely laminar over the range of Reynolds numbers of the present experiments. The plate was roughened by a wire, which was stretched across the flow, in contact with the plate. The diameters k of the

(1) I. Tani, R. Hama, S. Mituisi, T. Iriyama & M. Ueda, Boundary layer measurements on a flat plate in the 1·5 m wind tunnel (in Japanese). Jour. Aero. Res. Inst., No. 189 (1940)

wire were 0·25, 0·4, and 0·7 mm respectively, and the distance x of the wire from the leading edge was varied from 15 to 60 cm. When the wind speed V was low, the boundary layer was laminar all along the plate, but from a certain speed upward, the transition to turbulent flow was observed at that point where the wire was attached. Transition was detected by a sudden change in total pressure sufficiently close to the plate, the pressure being indicated by a small pitot tube with a flattened mouth of 1 mm external width and 0·3 mm depth, which was placed in contact with the plate at a point 70 cm behind the leading edge. A sample record of measurements is shown in Fig. 1, the final

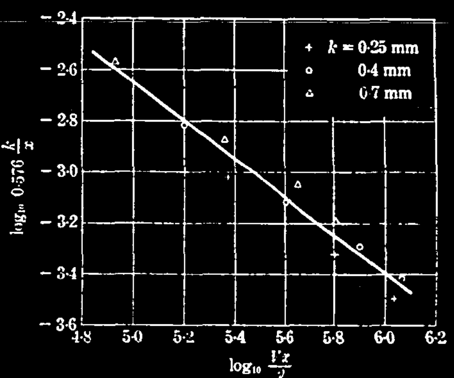

Fig. 2. Variation of the critical height of the excrescence with Reynolds number for a flat plate.

results being summarized in Fig. 2, in which $0\cdot576(k/x)$ is plotted in a logarithmic scale against Vx/ν, V being the wind speed corresponding to the kink of the curve of total pressure as shown in Fig. 1. By drawing a straight line of the slope $-3/4$ through the measured points, we get 13 for the constant K in the relation $0\cdot576(k/x) = K(Vx/\nu)^{-\frac{3}{4}}$.

Experiments on a symmetrical aerofoil.

When the pressure varies along the surface of a body, as for example an aerofoil, a similar expression, although not in explicit form, may be obtained for the relation between the magnitude of the permissible roughness and the Reynolds number. With the aid of Pohlhausen's solution[1] of boundary layer equations, we get

$$v_*^2 = \frac{\nu U}{\delta}\left(2+\frac{\lambda}{6}\right),$$

where

$$\lambda = \frac{\delta^2}{\nu}\frac{dU}{ds},$$

δ is the thickness of the layer, U the potential velocity outside the layer, and s the distance along the surface measured from the forward stagnation point. Constructing a Reynolds number R from the chord length t and the velocity of the undisturbed flow V, we have

$$\frac{v_*^2}{V^2}R^{\frac{1}{2}} = \frac{U}{V}\left(2+\frac{\lambda}{6}\right)\left[\frac{1}{\lambda}\frac{d(U/V)}{d(s/t)}\right]^{\frac{1}{2}},$$

which is a function of s/t only, so far as the curve of U/V is independent of R. Writing, therefore,

$$A\left(\frac{s}{t}\right) = \frac{v_*}{V}R^{\frac{1}{4}},$$

the permissible height of excrescence k is given by

$$A\frac{k}{t} = KR^{-\frac{3}{4}}.$$

In order to determine the constant K, a wire was attached to the surface of a symmetrical aerofoil of 0·8 m span and 1·2 m chord, fitted

(1) K. Pohlhausen, Zur näherungsweisen Integration der Differentialgleichung der laminaren Grenzschicht. Z.A.M.M. Bd. 1 (1921), S. 252.

with end plates 1·4 m × 0·6 m, and set at zero angle of incidence in the 1·5 m wind tunnel. The section of the aerofoil, L.B. 24, has a maximum thickness of 10 per cent of the chord at mid-chord, and the equation of the contour as given by $y = 0{\cdot}083666\, x^{\frac{1}{2}} + 0{\cdot}022518\, x - 0{\cdot}081678\, x^2$ for that point from $x = 0$ (leading edge) to $x = 0{\cdot}5$, and $y = 0{\cdot}001 + 0{\cdot}250$

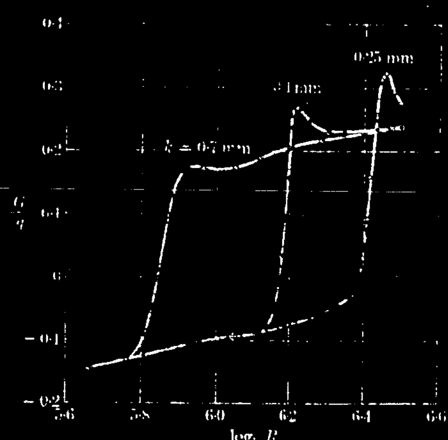

Fig 3. Variation with Reynolds number of the total pressure G^*, which is indicated by a small pitot tube in contact with the surface of the aerofoil L.B. 24. Wires of various diameters k are placed at 10 per cent of the chord from the leading edge. $q = (1/2)\rho V^2$.

$(1-x) - 0{\cdot}412(1-x)^2 + 0{\cdot}210(1-x)^3$ for that point from $x = 0{\cdot}5$ to $x = 1$ (trailing edge). The object of the unusually backward situation of the maximum thickness was to delay the transition which, on a smooth aerofoil, was actually observed as far back as 80 per cent of the chord from the leading edge.(1) Wires of various diameters ($k = 0{\cdot}25$, $0{\cdot}4$, $0{\cdot}7$ mm) were stretched parallel to the span, in contact with the surface, at 10 per cent of the chord from the leading edge. Transition was

(1) I. Tani & S. Mituisi, Contributions to the design of aerofoils suitable for high speeds. Rep. Aero. Res. Inst., No 198 (1940).

detected by the sudden change in total pressure as indicated by a pitot tube with a flattened mouth of 2·7 mm external width and 0·9 mm depth, which was placed in contact with the surface at 50 per cent of the chord from the leading edge. The results of measurements are shown in Fig. 3.

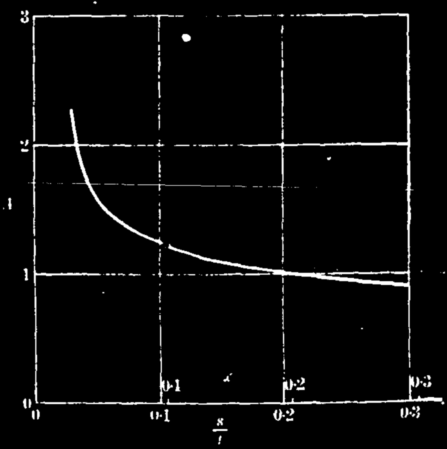

Fig. 4. Function A for L.B. 24.

Applying Pohlhausen's method[1] to the theoretically calculated distribution of U/V, we get the values of function A, as shown in Fig. 4. Since A is 1·23 for that point where the wire was attached ($x = 0{\cdot}1$), the value $1{\cdot}23(k/t)$ is plotted in a logarithmic scale against R in Fig. 5, R being the Reynolds number corresponding to the kink of the curve as given in Fig. 3. It will be seen that although the measured points are on a straight line of the slope $-3/4$, they give $K = 15$, which is somewhat larger than the value found for the flat plate. Although the reason for the disagreement in the values of K for the flat plate and the aerofoil is not clearly understood, it may probably be owing to the

(1) The calculation was kindly worked out by Mr. T. Noda at the request of the writers, who take this opportunity of expressing their best thanks.

fact that the transition is somewhat delayed by the negative pressure gradient over the forward part of the aerofoil.

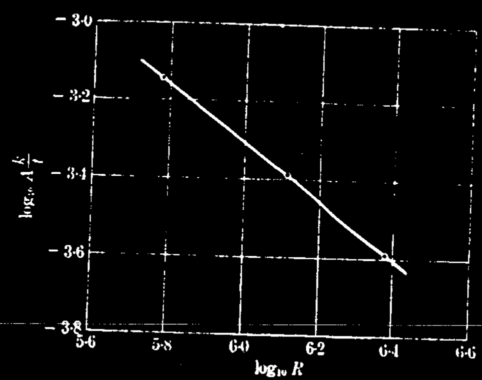

Fig 5. Variation with Reynolds number of the critical height of the excrescence at 10 per cent of the chord from the leading edge of L.B. 24.

Concluding remarks.

The experiments showed that the permissible roughness k in the laminar boundary layer is given by $k(\tau_0/\rho)^{\frac{1}{2}}/\nu = K$, where τ_0 is the shearing stress at the surface, and the value of K is 13 for the flat plate, and 15 for the symmetrical aerofoil. For practical application, the lower value may be assumed for K, because even should we err in the result, we shall be on the safe side. The permissible roughness then is given by

$$\frac{k}{t} = \frac{13}{A}\left(\frac{Vt}{\nu}\right)^{-\frac{3}{4}},$$

where V is the velocity of the undisturbed flow, t the reference length, such as the chord length, and $A\left[= (Vt/\nu)^{\frac{1}{4}}(\tau_0/\rho)^{\frac{1}{2}}/V\right]$ depends on the shape of the body as well as on the position of the excrescence. Should the excrescence happen to be in a region of falling pressure, although

A may be calculated with sufficient accuracy by Pohlhausen's method, a fairly satisfactory result may also be obtained by assuming the velocity distribution across the boundary layer to be the same as that on a flat plate, whence

$$A = 0\cdot595\left(\frac{U}{V}\right)^{\frac{3}{4}}\left[\int_0^{\frac{s}{t}}\left\{\frac{U(s')}{U(s)}\right\}^{8\cdot18} d\left(\frac{s'}{t}\right)\right]^{-\frac{1}{4}}.$$

In conclusion, the writers wish to express their thanks to Mr. T. Iriyama and Mr. M. Ueda for their assistance in the wind tunnel experiments.

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